

TESTING OF A 2-KILOWATT WIND-ELECTRIC SYSTEM FOR WATER PUMPING

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ABSTRACT

A 2-kilowatt (3.3 m rotor diameter) wind-electric system has been tested for pumping water at the USDA-ARS Laboratory in Bushland, TX. This wind-electric system consisted of a wind turbine, controller, submersible motor, and a centrifugal pump. A total of 9 configurations of the baseline wind turbine were tested from Feb. 3, 1999 until April 19, 2000. Changes in the wind turbine configuration included: 2 different yaw axis offsets, 4 different tails, and 3 different pitch settings. Configuration #8 achieved a peak power coefficient of 0.46 (compared to 0.34 for Configuration #7), and the cut-in wind speed was 4 m/s (5 m/s for Configuration #7). The peak system efficiency of Configuration #8 was 17%, and the daily water volume for Configuration #8 at a 30 m head ranged from 28 cubic meters to 42 cubic meters (5 to 6 m/s average wind speed). However, Configuration #7 demonstrated reliability while Configuration #8 had a problem with the permanent magnet alternator overheating at high wind speeds. Configuration #9 having a lower furling wind speed may help to alleviate the problems with #8 without reducing the water pumping performance significantly.

INTRODUCTION

Wind-electric systems have been tested at the USDA-ARS in coordination with WTAMU-AEI since 1988. The four key issues for any remote water pumping system are performance, cost, reliability, and maintainability. Maintenance of the wind-electric system's centrifugal motor and pump is less than the mechanical windmill's piston pump. The reliability of the wind-electric system has been worse than a mechanical system due to reliability problems with the controller. However, a newly designed ARS/AEI wind-electric pump controller has demonstrated that wind-electric controllers can be reliable (Ling et al., 2000). The cost of wind-electric systems has been shown in some cases to be cheaper than new mechanical windmills (Vick et al., 1997). Mechanical windmills have always had a lower cut-in wind speed than wind-electric systems due to the mechanical rotor's high solidity and little loss in efficiency as rotor mechanical power is directly used in the mechanical pumping of the water (Vick et al., 1997 and Vick et al., 1999). The high solidity of the mechanical rotor also results in a better system efficiency than wind-electric systems at low wind speeds (Vick et al., 1997). The Havatex¹ 2000 wind turbine uses advanced airfoils (NREL S822 and S823) and a Glauert chord and near Glauert twist distribution. The Havatex Permanent Magnet Alternator (PMA) design includes rare earth permanent magnets with a very small gap between the magnets and stator. These improvements have resulted in lowering the cut-in wind speed and obtaining a system efficiency at moderate wind speeds comparable to the mechanical windmill's system efficiency at low wind speeds.

¹ The mention of trade or manufacture names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA - Agricultural Research Service.

A total of nine wind turbine configurations of the Havatex 2000 wind turbine have been tested. Seven configurations were tested in 1999 and 2 configurations were tested in 2000. Most of the testing in 1999 has been reported (Vick et al., 2000), but substantial improvements in power and pumping performance were seen during the testing of the two configurations in 2000 and those results are reported in this paper. During the 1999 testing the water pumping performance degraded substantially for all wind speeds when the pitch setting was increased from 4.5 to 6.5 degrees. A more positive pitch setting means the angle-of-attack of the blade airfoils have decreased. It should be noted here that when the pitch setting was changed, a new set of blades had to be fabricated. Although the Havatex 2000 had been tested at a pitch setting of 3 degrees prior to testing at the USDA laboratory in Bushland -- that testing implied a higher cut-in wind speed compared to a pitch setting of 4.5 degrees. Despite this result, testing a set of 3 degree pitched blades appeared to be the next logical step. When the 3 degree pitch blades were tested, not only was the cut-in wind speed lower, but the power was increased at all wind speeds. Higher power at the lower wind speeds was a good thing, but higher power at the higher wind speeds resulted in excessive heating of the PMA magnets which caused the magnetic strength of the magnets to decrease by at least 50%. Another configuration was then tested which furled at lower wind speeds and took advantage of the increased power at lower wind speeds while limiting the power at higher wind speeds which protected the PMA from excessive heating. Unfortunately the magnets used to replace the degraded magnets appear themselves to be degraded although not as bad as the replaced magnets, and this led to unreportable water pumping performance results for this configuration. Although the future of this wind-electric system is uncertain, the Havatex 2000 has demonstrated an improvement in wind-electric system development.

DESCRIPTION OF WIND-ELECTRIC SYSTEM

The Havatex 2000 wind-electric system is a 3-bladed upwind, variable speed, horizontal axis wind turbine which uses horizontal furling for overspeed control. (See Figure 1). The rotor diameter is 3.3 m and uses two NREL HAWT airfoils (S822 and S823). The Havatex 2000 is rated at 2 kW at a wind speed of 11.5 m/s (sea level standard day conditions). The blades have a fairly linear chord distribution, but a non-linear twist distribution. The blades are made from epoxy prepregs with a foam core and are fixed to the hub with bolts perpendicular to the rotor axis (similar to a large utility scale wind turbine). For wind turbines below 10 kW these features (NREL airfoils, blade composition and blade attachment to hub) are unique. The wind turbine generates variable-voltage, variable-frequency, 3-phase AC electricity using a permanent magnet alternator (PMA). The Havatex PMA has 18 poles and uses rare earth magnets. The magnets are located on the main shaft and the stator is between the magnets and the outside metal container -- 0.7 mm gap between the magnets and the stator. This PMA configuration later was shown to have problems dissipating the generator heat for some of the configurations tested. The electricity generated by the PMA is conducted down the tower via a slip ring assembly and wiring harness. The total weight of the wind turbine is 82 kg (180 lb).

The Havatex 2000 was tested with two different controllers -- the Havatex 2000 controller and the ARS/AEI controller. Several times during the testing a 40 Ω / 20 μ F electrical load was tested, and no controller was connected between the wind turbine and this electrical load. The Havatex 2000 controller is energized from the wind turbine, so it does not require a battery. Four frequencies are used by the controller to control the operation of the wind turbine: low frequency cut-in, low frequency cut-out, high frequency cut-in, and high frequency cut-out. The controller disconnects the wind turbine from the pump motor for all frequencies below low frequency cut-out. When the frequency reaches low frequency cut-in the controller connects the pump motor to the wind turbine. At high frequency cut-out the controller disconnects the pump motor from the wind turbine. The wind turbine is not reconnected to the pump motor until the frequency at high frequency cut-in is reached. These frequency settings are set by the

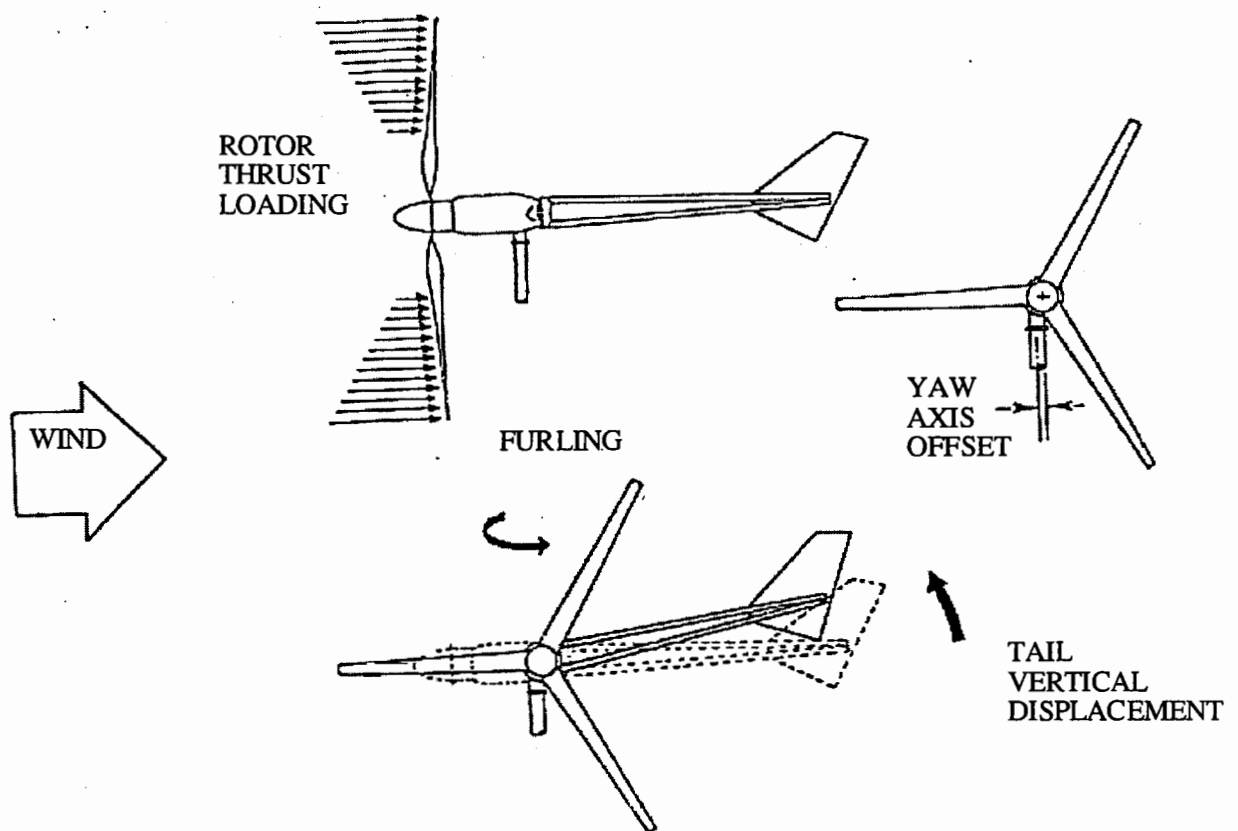


Figure 1. Horizontal Furling of a Havatex 2000 Wind Turbine.

manufacturer in the microchip and can not be altered by the user. Some typical frequency settings used were:

- 1) low frequency cut-in = 40 Hz
- 2) low frequency cut-out = 30 Hz
- 3) high frequency cut-in = 80 Hz
- 4) high frequency cut-out = 85 Hz

The controller uses solid state relays and incorporates three working capacitors for power factor correction which results in the pump motor running efficiently without needing an inverter. During the testing, additional solid state relays were included to allow a resistive/capacitive dump load to be added at the high frequency cut-out which was intended to reduce the wind turbine rpm in high winds. The dump load used was $40 \Omega / 20 \mu\text{F}$. The Havatex 2000 controller was tested from Nov. 1, 1999 until Dec. 10, 1999. On Dec. 10, 1999 some electrical components in the controller were damaged in winds in excess of 20 m/s. After that time the ARS/AEI controller was used in testing when submersible motors and centrifugal pumps were tested. The ARS/AEI controller is described in Ling, et al., 2000. The frequency settings of the ARS/AEI controller are adjustable, and two additional frequency settings (dump load cut-in and cut-out) are available besides the frequency settings mentioned above. In addition, the ARS/AEI controller has logic for monitoring the voltage-to-frequency ratio to protect the pump motor and the PMA. During the water pumping performance testing in 2000, the ARS/AEI controller logic was modified when the dump load was added to match the method used by the Havatex controller. In normal operation of the ARS/AEI controller, water was still pumped because the pump motor was still connected when the dump load was added. However, when the dump load was added by the Havatex controller, the pump motor

was disconnected -- this occurred at high frequency cut-out. At high frequency cut-in for the Havatex controller, the dump load was disconnected and the pump motor was reconnected. The logic of the ARS/AEI controller which monitors the voltage-to-frequency ratio was also disabled during the testing in 2000.

The submersible motors tested were rated at 1.5 and 1.1 kW. All the motors were Franklin Electric¹ 3-phase, 230 V, 10 cm diameter submersible motors. The centrifugal pumps tested included a 1.1 kW, 9-stage pump and a 0.75 kW, 19-stage pump. All the pumps were Grundfos¹ 10 cm diameter pumps.

For a description of the instrumentation and data acquisition system, see (Vick, et al., 2000).

RESULTS

Table 1 shows the configurational changes which were tested on the Havatex 2000. The majority of the changes had to do with the tail design but changes were also made to the yaw axis offset and the pitch angle. The tail and offset changes were meant to modify the furling behavior of the wind turbine, and the pitch angle changes were done to improve power or water pumping performance at low wind speeds.

Table 1. Configurations Tested on Havatex 2000 Wind Turbine at Bushland, TX.

<u>HAVATEX 2000 WIND TURBINE CONFIGURATION DESCRIPTION</u>					
<u>Configurations</u>	<u>Tail Used</u>	<u>Yaw Axis Offset</u>	<u>Pitch Angle</u>	<u>Additional Tail Bumpers</u>	<u>Dates Tested</u>
Configuration 1	Tail 1	25 mm (1")	4.5 deg	No	Feb. 3, 1999 - Mar. 10, 1999
Configuration 2	Tail 2	"	"	"	Mar. 10, 1999 - Apr. 1, 1999
Configuration 3	"	"	"	Yes	Apr. 1, 1999 - Apr. 14, 1999
(Turbine down for redesign)					
Configuration 4	Tail 3	31 mm (1.22")	4.5 deg	Yes	Apr. 28, 1999 - May 18, 1999
Configuration 5	Tail 2	"	"	"	May 18, 1999 - July 6, 1999
Configuration 6	Tail 4	"	6.5 deg	"	July 6, 1999 - July 29, 1999
Configuration 7	"	"	4.5 deg	"	July 29, 1999 - Dec. 10, 1999
(Turbine down due to controller problem)					
Configuration 8	Tail 4	31 mm(1.22")	3.0 deg	Yes	Jan. 7, 2000 - Feb. 23, 2000
(Turbine down due to PMA magnet degradation)					
Configuration 9	Tail 3	31 mm(1.22")	3.0 deg	Yes	Mar. 9, 2000 - Apr. 19, 2000

TAIL DESCRIPTION

<u>Tails</u>	<u>Length of Tail Boom</u>	<u>Wt. of Tail Boom</u>	<u>Wt. of Tail Vane</u>	<u>Total Tail Wt.</u>	<u>Tail Moment Arm C.G.</u>	<u>Tail Moment Arm C/4 Tail</u>
Tail 1	82.9 cm (72")	5.30 kg	2.71 kg	8.01 kg	109.2 cm	158 cm
Tail 2	"	"	3.48 kg	8.78 kg	115.6 cm	158 cm
Tail 3	132.1 cm (52")	6.20 kg	"	9.68 kg	80.3 cm	107 cm
Tail 4	157.5 cm (62")	7.22 kg	"	10.70 kg	86.7 cm	132 cm

Most of the test results collected in 1999 have already been reported (Vick et al., 2000). Figure 2 shows the power curves for several configurations tested in 1999. No controller was used to develop these power curves, and a constant electrical load of 40 Ω and 20 μ F was applied. The power curve for Conf. 3 was the best power curve, but that configuration resulted in a failure of all three blades due either to the

blades not being able to handle the high loads at high rpm which occurred at high wind speeds or the violent yawing behavior or a combination of both. During the next three months modifications in the tail and the yaw axis offset were tested in order to obtain a gentle furling behavior and keep the blade rpm from getting too high by lowering the furling wind speed. In addition, the strength of the blades, yaw shaft, tail boom, and blade bolts were increased.

Figure 3 shows the final power curve (Conf. #7) tested in 1999 and power curves of the two configurations tested in 2000. Again, these power curves were obtained by applying a constant electrical load of $40\ \Omega / 20\ \mu\text{F}$ (no controller). The only difference between Conf. #7 and Conf. #8 is Conf. #7 had its blades pitched at 4.5 degrees and Conf. #8 had its blades pitched at 3 degrees. Both the power and the power coefficient (C_p) curves were increased dramatically with the decrease in pitch angle. As was mentioned earlier, the high power at high wind speeds for Conf. #8 resulted in excessive heating of the PMA which caused the magnets to lose at least half of their magnetic strength. The magnets' magnetism does not appear to have been degraded until halfway through the water pumping data collected on Conf. #8 which was collected after this data. The difference between Conf. #9 and Conf. #8 is the tail boom length was decreased from 1.55 m to 1.3 m. The power at the low wind speeds was about the same for Conf. #9 and Conf. #8, but the power at the higher wind speeds was decreased (exactly the result desired). It will be noticed at the low wind speeds the C_p of Conf. #9 is a little below that of Conf. #8. Since the magnets used to replace the degraded magnets were degraded themselves, this is the reason the C_p of Conf. #9 at low wind speeds is less than that of Conf. #8.

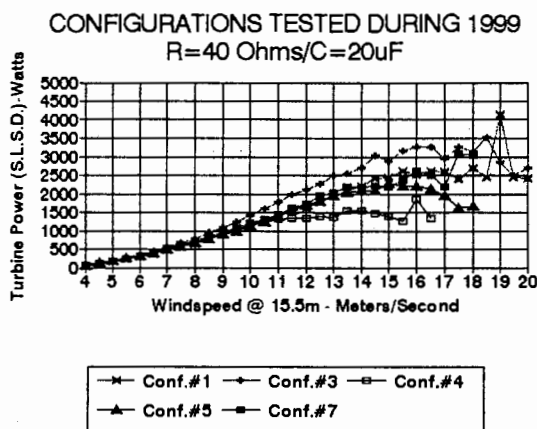


Figure 2. Power Curves of Havatex 2000 Configurations Tested during 1999.

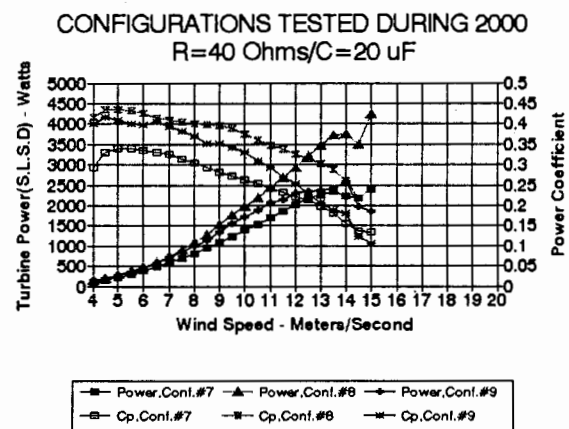


Figure 3. Power Curves of Havatex 2000 Configuration Tested during 2000.

The effect of changing the electrical loading on power and C_p is shown in Figures 4 and 5. The C_p during the pump motor electrical loading is below that of the $40\ \Omega / 20\ \mu\text{F}$ electrical loading for wind speeds below 7 m/s (Figure 4) and 6 m/s (Figure 5) because the wind turbine is trying to overcome the starting torque of the pump motor. The C_p during the pump motor electrical loading is actually better than the $40\ \Omega / 20\ \mu\text{F}$ electrical loading in the wind speed range of 7 to 13 m/s (Figure 4) and 6 to 9 m/s (Figure 5). Above 9 m/s (Figure 5) the C_p during the pump motor electrical loading is a little below the $40\ \Omega / 20\ \mu\text{F}$ electrical loading, but this is due to the magnetism of the magnets just beginning to deteriorate. The main difference between these two configurations is Conf. #8 had a higher peak C_p with a pump motor electrical loading and Conf. #7 had a higher peak C_p for the $40\ \Omega / 20\ \mu\text{F}$ electrical loading.

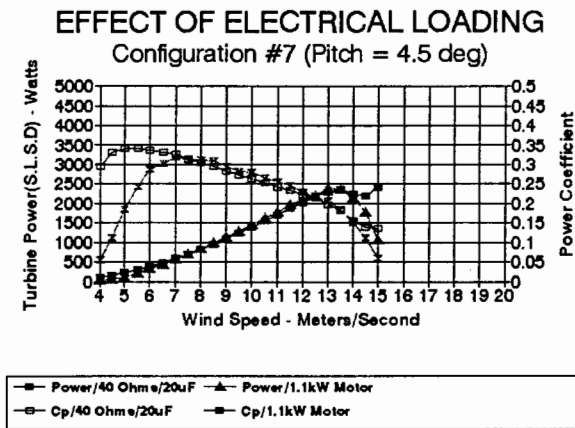


Figure 4. Effect of Electrical Load on Power And Cp of Configuration #7.

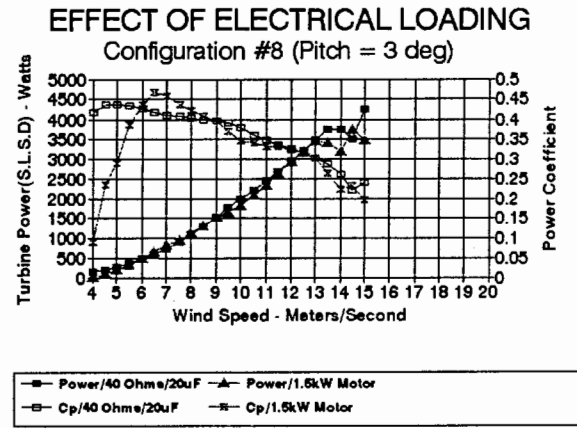


Figure 5. Effect of Electrical Loading on Power Power and Cp of Configuration #8.

Figure 6 shows the effect of tail boom length and pitch angle on the furling wind speed. Configurations #4, #5, and #7 were at a pitch setting of 4.5 degrees and Configurations #8 and #9 were at a pitch setting of 3 degrees. While tail boom length appears to have the most effect on furling wind speed (longer tail boom has higher furling wind speed), decreasing the pitch angle (or going to a more optimum angle-of-attack) has the effect of also increasing the furling wind speed.

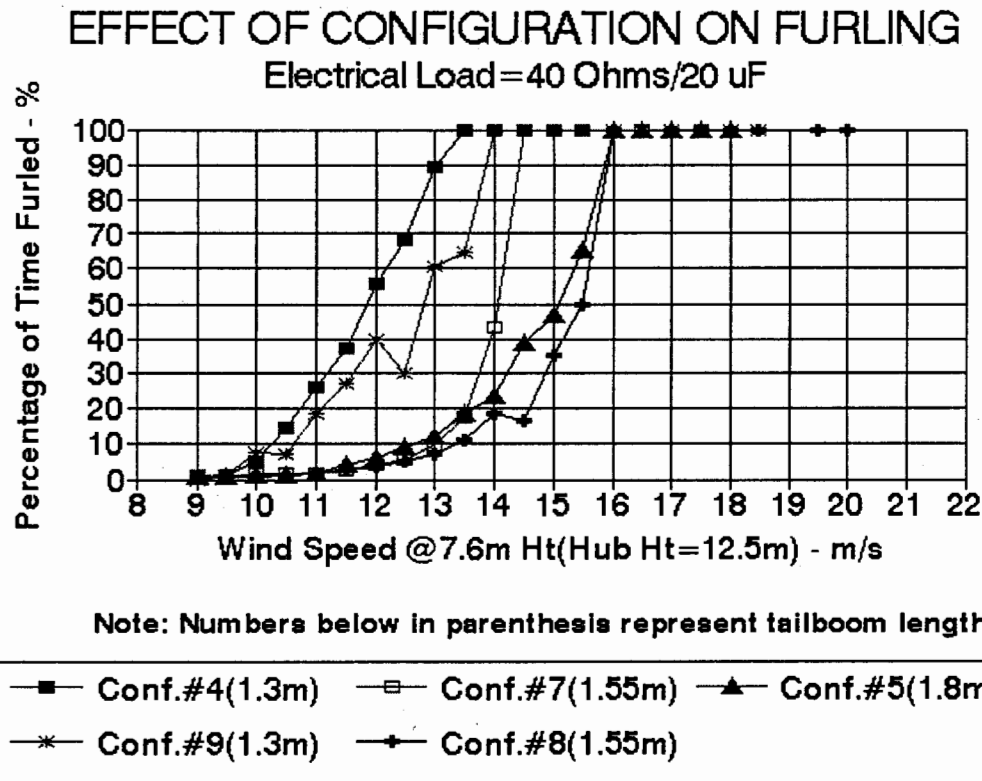


Figure 6. Effect of Havatex 2000 Configuration on Furling for an Electrical Load of 40 Ohms/20uF.

The effect of pitch angle on flow rate when the wind turbine was connected to a 1.5 kW motor / 1.1 kW 9-stage pump at a 30 m head is shown in Figure 7. Conf. #8 (pitch angle = 3 deg) has an earlier cut-in wind speed (4 m/s) than Conf. #5 (pitch angle = 4.5 deg) which has a cut-in wind speed of 5 m/s. The peak flow rate for both configurations occurs after the motor loses synchronization with the wind turbine and does not have anything to do with the furling wind speed. The average frequency of both configurations is shown on the same graph. It will be noticed that when the frequency reaches 50 Hz the peak flow rate is reached. The wind turbine actually loses synchronization with the motor at 70 Hz, but as the frequency increases above 50 Hz the chance of a gust increasing the frequency above 70 Hz increases. Conf. #9 when tested with good magnets should be very similar to that of #8 except at higher wind speeds the flow rate will be even higher as the lower furling wind speed will keep the wind turbine synchronized with the motor more often.

The effect of pitch angle on system efficiency is shown in Figure 8. The peak system efficiency for the lower pitch angle (Conf. #8) is 17% compared to 12% for the higher pitch angle (Conf. #5). System efficiency is related to flow rate as power coefficient is related to power and is a good way to compare other wind-electric systems. A system efficiency of 17% is the highest measured at the USDA laboratory for wind-electric systems since we started testing these systems twelve years ago. A 17% system efficiency at 7 m/s is about the same as that measured by mechanical systems at 4 m/s, but is better since the power in the wind is much higher at 7 m/s.

HAVATEX 2000(Corr. to const. 30m head)
1.5kW Motor, 1.1kW 9-stg Pump, 50uF

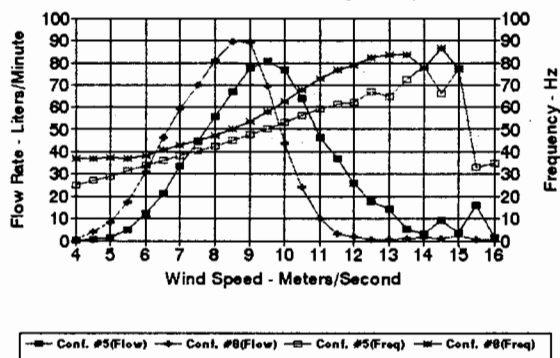


Figure 7. Effect of Pitch Angle on Flow Rate
And Frequency of Two Configurations
Tested on Havatex 2000.

HAVATEX 2000(Corr. to const. 30m head)
1.5kW Motor, 1.1kW 9-stg Pump, 50uF

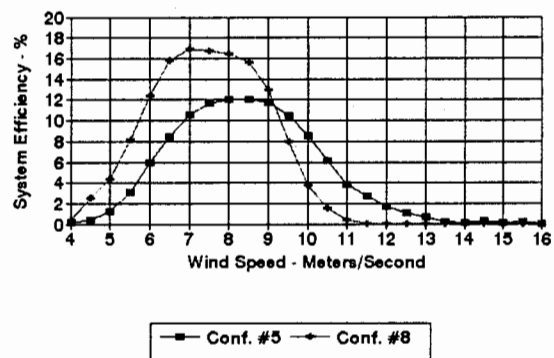


Figure 8. Effect of Pitch Angle on System
Efficiency of Two Configurations
Tested on Havatex 2000.

In order to determine the application of this wind-electric system for water pumping, the monthly daily water volume pumped was determined. Hourly average wind speeds have been collected at Bushland at a 10 m height since 1983. Figure 9 shows the monthly average wind speed at Bushland for a 10 m height from 1983 to 1999. Although most wind-electric systems are installed on taller towers, this height is more appropriate since this wind turbine was meant for lower wind speed regimes and a 10 m height in Bushland is equivalent to 20 and 30 m heights in lower wind regimes. Multiplying the average monthly wind distributions for Bushland at a 10 m height (1983 - 1999) by the flow rate curves in Figure 7, the monthly average daily water volumes were obtained as shown in Figure 10. Obviously pitching the blades at 3 degrees instead of 4.5 degrees was much better since the daily water volume was almost doubled in August. Since August is usually the lowest wind month and for livestock watering it is also one of the highest usage months due to the high temperatures, the amount of water pumped in August usually determines whether the system will meet the needs of the user. August is also one of the most important months for irrigation since plants need more water for growing during this time.

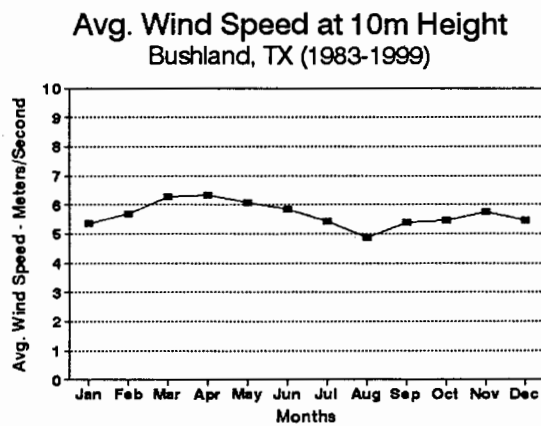


Figure 9. Average Wind Speed at 10 m Height Near Bushland, TX (1983-1999).

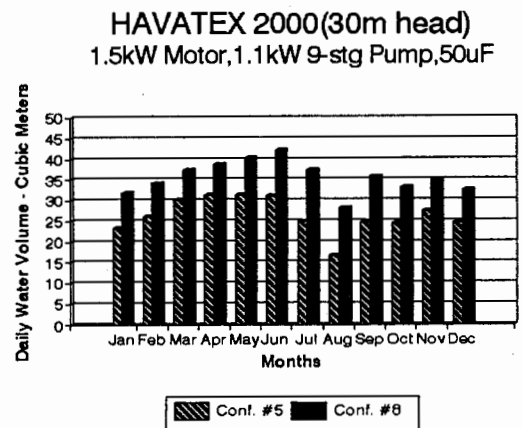


Figure 10. Daily Water Volume of Two Configurations Tested on Havatex 2000 for a 30 m Head.

CONCLUSIONS

By using advanced airfoils and a permanent magnet alternator with rare earth magnets, the system efficiency of a wind-electric system can be increased to 17% (the highest system efficiency ever measured at the USDA laboratory in Bushland since testing began twelve years ago). The cut-in wind speed of 4 m/s is also the lowest cut-in wind speed measured for a wind-electric system pumping at a 30 m head. The combination of these two characteristics (higher system efficiency and lower cut-in wind speed) make wind-electric systems more likely to be the best choice for many remote water pumping applications. Although pitch angle is not as important as tail boom length, it was shown to have a significant effect on furling wind speed. A peak power coefficient of 0.46 was measured with a blade using NREL S822 and S823 airfoils which is the highest power coefficient measured at Bushland for any wind-electric water pumping system.

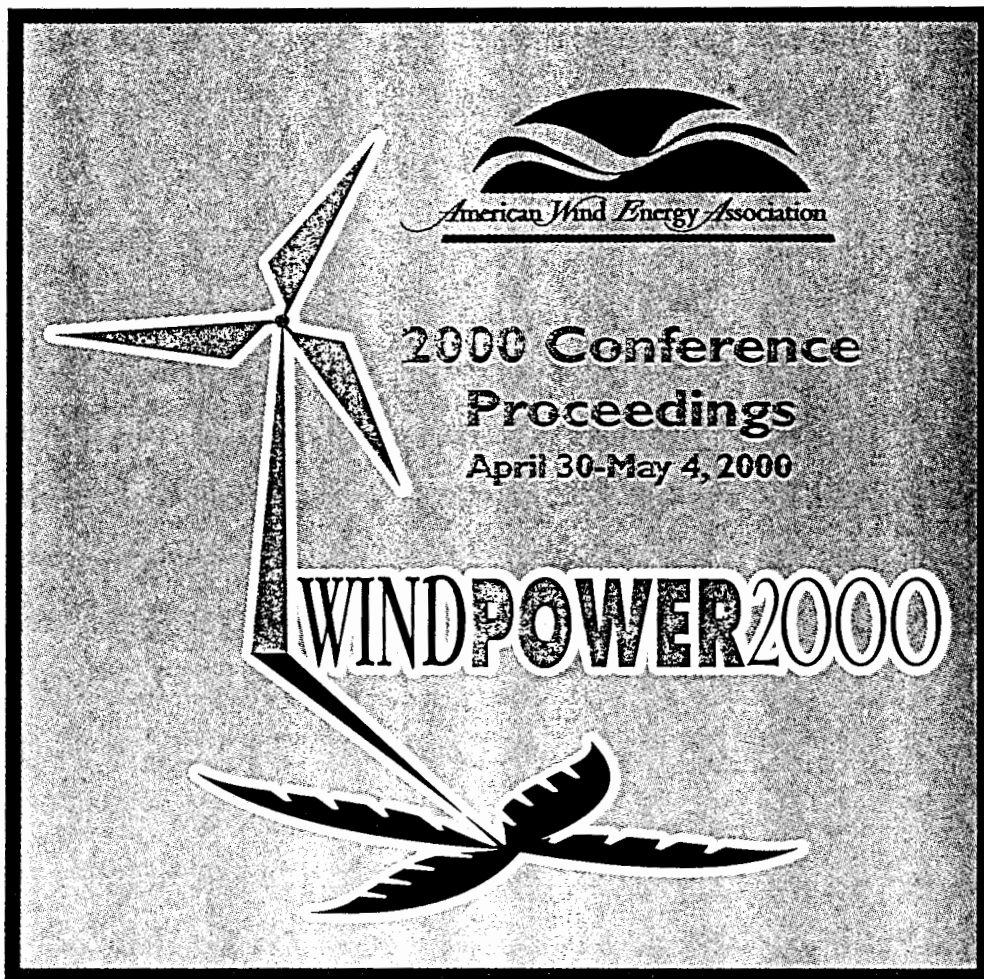
The Havatex 2000 PMA was seen to have excessive heating problems which caused a substantial loss in the strength of the rare earth magnets if the measured power stayed in the 3 to 5 kW range for any sustained length of time. Although the last configuration tested had a lower furling wind speed, there was still some concern that over time the magnets may lose their strength. Some way of venting the heat out of the alternator housing would be desirable. Another possibility is to increase the power rating of the generator by increasing the size of the wire in the stator which would allow more current to flow through the wire without generating as much heat.

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